Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	
Reassessment of Federal Communications Commission Radiofrequency Exposure Limits and Policies	ET Docket No. 13-84
Proposed Changes in the Commission's Rules Regarding Human Exposure to Radiofrequency Electromagnetic Fields	ET Docket No. 03-137
To: The Commission	

JOINT COMMENTS OF MOMENTUM DYNAMICS CORPORATION AND OAK RIDGE NATIONAL LABORATORY

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Momentum Dynamics Corporation and Oak Ridge National Laboratory submit these Joint Comments on the Commission's Notice of Inquiry ("NOI") portion of the above captioned proceeding to address the Commission's inquiry as to whether it should explore actions to control radiofrequency exposure between the frequencies of 0 to 100 kHz. The Joint Parties urge that the Commission not consider adopting radiofrequency exposure limits below 100 kHz.

No health or safety reason would justify such an extension and the likely administrative, economic, and opportunity costs would be significant. According to the evidence presented in IEEE C95.1 and IEEE C95.6, observable biological responses to electrical and magnetic fields at frequencies below 100 kHz occur at field intensities only well in excess of those expected in inductive wireless power transmission systems.

Nevertheless, should the Commission decide to adopt limits below 100 kHz, the limits should be based upon the latest relevant IEEE Standards, C95.1-2005, C95.6-2002, and C95.7-2005. The reasons for strongly preferring these IEEE standards are detailed in the study appended to these comments.

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JOINT COMMENTS OF MOMENTUM DYNAMICS CORPORATION AND OAK RIDGE NATIONAL LABORATORY

Momentum Dynamics Corporation ("Momentum Dynamics") and Oak Ridge National Laboratory ("ORNL") (together, the "Joint Parties") hereby submit Comments on the Commission's Notice of Inquiry ("NOI") portion of the above captioned proceeding[1] addressed to the Commission's inquiry as to whether it should explore actions to extend its rules to control radiofrequency exposure between the frequencies of 0 to 100 kHz.[2] The Joint Parties urge that the Commission not consider extending radiofrequency exposure limits below 100 kHz for the reasons set forth below and in the appended statement. No health or safety reason would justify

[1] *First Report and Order, Further Notice of Proposed Rule Making and Notice of Inquiry*, 28 FCC Rcd 3498 (2013).
[2] *Id.* at 3580, ¶ 229.

such an extension and the likely administrative, economic, and opportunity costs would be significant. Nevertheless, should the Commission decide to adopt limits below 100 kHz, the limits should be based upon the latest relevant IEEE Standards, C95.1-2005, C95.6-2002, and C95.7-2005, for the reasons detailed in the study appended to these comments.

Introduction

Resonant induction wireless power transmission is a key enabling technology for electric vehicle acceptance and ultimately electric, automated highways. This emerging technology relies upon use of frequencies below 100 kHz for the safe and efficient transfer of power.

Momentum Dynamics is a technology development company located near Philadelphia, Pennsylvania engaged in developing the technology and business structures for resonant wireless power transmission, with an emphasis on automotive and commercial electric vehicle applications. Oak Ridge National Laboratory (ORNL) is a science and technology laboratory managed for the U.S. Department of Energy by UT-Battelle, LLC with an inherent interest in resonant wireless power transmission as part of its charter to develop and extend scientific and technical knowledge for national and societal benefit.

Background

Resonant induction wireless power transfer is an emerging technology that promises significant societal benefits through aiding and enabling near term widespread adoption of electric vehicles as economical and environment-friendly alternatives to conventional internal combustion engine vehicles fueled by petroleum.

Alternative Vehicle Mandate

Numerous federal and state mandates have been adopted to promote policies favoring alternative fuels and alternative fuel vehicles. Prominent among these is Executive Order 13514, which requires the replacement of internal combustion engine vehicles with alternative fuel vehicles on all federal properties.[3] Vehicles driven by compressed natural gas, biofuels, and battery electric vehicles all come within the scope of these alternative fuel mandates but each has unique advantages and disadvantages.

Natural gas is plentiful and comparatively inexpensive relative to liquid petroleum fuels, but requires the purchase of an expensive fueling compressor as well as connection to an industrial sized natural gas pipeline. The effective cost of natural gas also must include increased maintenance requirements. Furthermore, natural gas does not completely reduce the dependency on fossil fuels.

Biofuels are largely interchangeable with petroleum-based fuels, but are expensive and constrained by the availability of farmland, and the limited number of crops available per year. A fundamental issue is the poor energy conversion efficiency from incident sunlight to the final mechanical energy delivered.

Electric vehicles are extremely attractive in comparison, with cost per mile as little as one-tenth the cost of conventional petroleum fueled vehicles. In addition to the lower cost of energy and the existence of a ubiquitous distribution infrastructure, substantial additional savings accrue from the greatly reduced maintenance cost of electric motors when compared to that of internal combustion engines.

[3] *See,* Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance, http://www.gpo.gov/fdsys/pkg/FR-2009-10-08/pdf/E9-24518.pdf, and also http://www1.eere.energy.gov/femp/pdfs/eo13514_fleethandbook.pdf

Pure electric vehicles offer the compelling virtue of having zero tail pipe emissions, a highly desirable quality in both crowded urban environments and pristine wilderness areas. Gasoline and diesel fuels are known to be toxic and carcinogenic and indeed, diesel emissions recently have been associated with autism.[4] The elimination of vehicle tailpipe emissions is crucial to improving the environment generally and offers inarguable health benefits.

It is widely understood that the weakness of electrically powered vehicles comes from their poor operational range. Current batteries do not have sufficient energy density to allow all day operation or driving ranges comparable to that of gasoline and diesel-fueled vehicles. Furthermore, overnight charging cannot address the needs of commercial vehicles that operate 18 – 24 hours a day or which have unpredictable or variable duty requirements. While battery energy density continues to improve, the rate of improvement has been slow. Near-term battery performance breakthroughs of reliable commercial scale cannot be expected. Consequently, electric vehicle adoption has been slow and an improved method of rapid and automated battery charging is needed to address the real needs of electric vehicle users. This is critical to both passenger-class and commercial-class electric vehicles.

Opportunity Charging

Battery range limitations can be mitigated or eliminated in many situations by wireless opportunity charging. For example, a bus or delivery truck running a regular route can be charged wirelessly while stopped to make a delivery or to pick up or drop off passengers. A full battery charge is not necessary; enough charge to get the vehicle to the next charging station is sufficient. Wireless charging is important because in many circumstances plug-in charging is

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[4] Volk HE, Lurmann F, Penfold B, Hertz-Picciotto I, McConnell R. Traffic-Related Air Pollution, Particulate Matter, and Autism. *JAMA Psychiatry.* 2013; 70(1):71-77. doi:10.1001/jamapsychiatry.2013.266.

impractical, such as when the vehicle driver cannot leave his position. Moreover, wireless charging is immune to weather and can be automated, making practicable charging under all weather conditions.

The scrap metal value of plug-in chargers and charger cords make them targets for vandals, and charger cords present a significant tripping hazard with significant legal liability and health risk. Commercial operators of electric vehicle fleets are seeking vehicle-charging solutions that will not present a tripping hazard for employees or a risk interference with moving conveyor belts and material handling equipment.

Well-designed wireless charging systems have AC grid-to-vehicle battery transfer efficiencies as high or higher than corded (wired) chargers; overall efficiencies in excess of 90% are now common in current generation inductive (wireless) chargers. With the ability to be embedded in pavement and use automatic vehicle recognition, wireless charging will extend driving range and improve battery life cycle costs.

Wireless Resonant Induction

Wireless resonant power transfer for battery electric vehicle charging consists of a high frequency inverter to excite a loosely coupled transformer. Primary and secondary side tuning effectively cancels leakage inductances that otherwise would result from loose coupling and thereby enhances power transfer across large gaps. Vehicle electronics can be as simple as a diode rectifier and filter or some form of power electronic converter. The result is efficient delivery of filtered DC charging current to vehicles' regenerative energy storage system.

Leakage Field Amplitudes

Leakage field is that fraction of the primary coil magnetic flux not linking the secondary, or capture coil, and which can become large as coil separation increases. Leakage fields have magnitude in direct proportion to the primary coil exciting current, the coil design, and degree of misalignment. To limit leakage and improve efficiency, resonant wireless charging of vehicles does not commence until the ground unit (ie, the primary induction coil) has positively identified the presence and the adequate coil-to-coil alignment of a vehicle equipped with a compatible wireless power receiving (*i.e.*, secondary) induction coil.

Measurements reveal that resonant induction wireless power systems have near background level exposures for vehicle passengers because the vehicle's metallic underbody provides excellent magnetic field shielding. Non-metallic body vehicles attain similar levels of shielding when a thin layer of conductive material, a thin metal sheet, or metallically coated plastic sheet is added. Required shield thickness depends upon material conductance and magnetic permeability.

Some of the laboratory experimental results performed by ORNL also revealed that the magnetic field on the vehicle floorboard, driver seat, and driver headrest are too small to measure due to the aluminum sheet backed coil enclosures and the vehicle chassis. In addition, when transferring relatively high power to the vehicle (5 to 8 kW), it was observed that the magnetic field at about 0.8 meters away from the center of the primary coil was less than 6 µTesla ("µT").

Momentum Dynamics' measurements of a laboratory development 20 kW system for use with buses showed magnetic flux field intensities at a distance corresponding to the vehicle body perimeter to be on the order of 25 µT, *however these measurements were taken in the laboratory* *without the vehicle present.* In an operational rather than laboratory setting[5] leakage fields are significantly reduced by the shielding effect of the bus frame, body and undercarriage.

The strongest fields are at ground level (*i.e.*, measured in-plane with the coil), moderating with increasing height and increasing horizontal separation from the ground mounted induction coil. Maximum human exposure occurs at foot level, standing against the vehicle side at minimum distance from the induction coil pair. Exposure intensity decreases with height, decreases sharply above knee level, and decreases quickly with increasing horizontal separation from the induction coil pair. Chest and head exposure levels are near background level.

Momentum Dynamics' direct measurements of vehicles equipped with a 20 kW wireless charging prototype confirm these results. The prototype vehicle was a repowered 2013 model year Ford E-450 12-passenger minibus with a plywood floor. The vehicle was converted to full electric operation by replacing the internal combustion engine with electric motors. Charging was accomplished by a pavement-mounted primary coil and a secondary coil mounted to the vehicle undercarriage, with a 12" vertical gap between the coils. (This gap remains constant during charging.) Operational frequency of the system was 23.5 kHz. An aluminum plate was integrated into the secondary coil housing as a means of shielding the vehicle. While operating at full power (20 kW), measurements confirmed that inside the vehicle the magnetic leakage flux showed background levels at all points inside the vehicle, including directly over the coil mounting position.[6]

For additional comparison, Momentum Dynamics used a consumer-grade induction kitchen stove to measure a magnetic flux field of about 20 μT at waist level at the edge of a six-

[5] *For example*, measured when the secondary coil is mounted to the vehicle and the primary coil is in the charging configuration under the vehicle, which is representative of ordinary operations.
[6] These measurements were taken in June 2013.

hob with one hob operating at full power (1800 watts). This result is in general accord with the extensive measurements made by Viellard, Romann, Lot, & Kuster.[7] We also measured maximum field intensity in excess of 2000 μT immediately above an active hob with the cooking utensil displaced to the side of the hob but sufficiently centered to activate the stove's magnetic pot detector. In fact, there are decades of experience with consumer-grade induction cooking appliances dating to the 1970's where human body exposure to alternating magnetic field leakage flux, incident mainly on the body core and close to the head, eyes, and brain, are far higher than the measurable leakage flux used in wireless vehicle charging devices. The operational frequencies of these induction cooking devices are normally between 25 and 75 kHz, which is consistent with the operating frequencies of the resonant inductive wireless power systems under development by both Momentum Dynamics and ORNL.

For reference to non-alternating magnetic fields, the intensity of the earth's magnetic field ranges from about 65 μT at the magnetic poles to about 25 μT near the equator. However, this is a largely continuous as opposed to an alternating field, and to the extent that it is continuous and non-fluctuating does not induce electrical eddy currents in the human body and therefore has little or no observable human biological effect.

[7] B-Field Exposure From Induction Cooking. Appliances, Foundation for Research on Information Technologies in Society, Clementine Viellard, Albert Romann, Urs Lott, and Niels Kuster. Zurich, July 2006 (revised July 2007)

Dynamic Induction Charging

Dynamic wireless charging of an electric vehicle has been demonstrated at ORNL. The demonstration consisted of an energized roadway mock-up employing a six-coil track in which the coils are sequenced in synchronism with the vehicle motion. Testing of dynamic wireless charging results in pulsing power to the on-board battery at a frequency dependent on vehicle speed, coil dimensions, and coil pitch. During vehicle passage the inherent misalignment to alignment sequence results in alternating real and reactive power levels, the reactive power component manifesting itself in the fringe field. Appropriate flux guides made from ferrite focus the field beneath the vehicle and metallic induction coil backing plates provide additional shielding so that field levels in the passenger cabin are in the range of background field levels.

With advanced radio communications and control a vehicle such as the autonomous driving taxi recently announced by Google is a prime candidate for wireless charging. Autonomous drive vehicles conceptually would be capable of finding a wireless charging station on their own and charging automatically.

Taken together, dynamic induction charging of moving vehicles, intelligent highway, and autonomous vehicle technologies potentially have transformational societal safety, environmental, and economic benefits. These are current and near-term emerging technologies; no major technological breakthroughs are needed. These combined technologies make automatic vehicle convoying possible, thereby greatly increasing highway vehicle, passenger and cargo capacity while improving safety and decreasing traffic congestion.

These emerging technologies also form the basis of a new mass transportation modality that makes use of existing highway infrastructure. Users would order a taxi using a smart phone.

The vehicle would drive itself to the embarkation point and convey the passengers to their destination. The vehicle would make use of wireless power transfer and grid electrical power on electrified highways with embedded induction coils. Tthe vehicle would revert to a relatively small onboard electric battery on non-electrified highways.

A transportation system such as this would have infinite spatial and temporal granularity. Start anywhere at any time and travel to anywhere by the shortest route arriving directly without intermediate stops or transfers. Although electrification of major highways would be expensive, by comparison urban light rail costs well over 100 million dollars per route mile largely due to costs of acquiring land, legal costs and new infrastructure design and construction costs. Electric, intelligent highway technology passenger- mile costs easily can be an order of magnitude less expensive than urban light rail. This possibility is evidenced by decades of support for intelligent highway design by the US Department of Transportation.[8]

Discussion

The Commission's radiofrequency electromagnetic field human exposure limits in the 100 kHz - 100 GHz range are predicated upon limiting or preventing thermal biological effects, *i.e.*, biological responses caused by local or generalized heating caused by radiofrequency exposure and subsequent heating. But at frequencies below 100 kHz human tissues are essentially transparent, radiofrequency absorption coefficients are very small, and thermally induced biological effects are not a serious concern.

There are, however, two non-thermal physical mechanisms for electromagnetically induced biological responses below 100 kHz, electric field induction and magnetic field

[8] For more information on the US Department of Transportation initiative into intelligent highways, *see*: http://www.its.dot.gov

induction. A conductive object exposed to a strong static electric field has positive charges induced on the side closest to the negative electric field source, and negative charges induced on the side closest to the positive field electric field source. If the electric field alternates, the induced charges alternate as well and an electric alternating current flows in the object. If the exposed object is a human body, an alternating electric field induces an alternating electrical current in the body and if the electric field intensity is sufficient, the induced body current can be large enough to cause spurious neural stimulation. The stimulation threshold depends upon frequency and nerve sensitivity. Electric field exposure limits at low frequencies set forth in IEEE C95.1, ICNIRP and in other relevant electromagnetic field exposure guidelines are intended to avoid neural stimulation.

Human bodies respond similarly when exposed to intense low frequency alternating magnetic fields except the resulting body currents are a result of magnetic, not electric induction. Low frequency magnetic fields induce eddy currents in the body that if sufficiently intense also can induce spurious neural stimulation.

The degree of neural stimulation is largely proportional to the eddy current magnitude and, ignoring body tissue electrical conductivity inhomogeneity, the largest body eddy currents, presuming worst-case magnetic field vector orientation, occur along the major and minor axis of the body torso where the induced eddy current loops have the largest enclosed area. Limbs and extremities have much smaller eddy current enclosed loop areas. Consequently eddy current amplitudes are much smaller and limb threshold magnetic field exposure limits are proportionally larger. Further technical discussion of magnetically induced currents and their biological effects is available in ICES IEEE C95.1, C95.6, reference documents by

Reilly *et al*,[9,10] and further discussed in the Appendix of this document.

Resonant induction wireless power relies upon strong, alternating magnetic fields. Associated electric field intensity is small even with the B-field time derivative included. For this reason these comments primarily address magnetic field exposure limits and are limited to magnetic fields that are sinusoidal or largely sinusoidal.

Human exposure to magnetic fields associated with induction wireless power transfer primarily is limited to the extremities that have higher response thresholds than the torso and head. Furthermore, magnetic field exposure drops off very quickly with increasing distance from the induction coils. Persons not standing immediately adjacent to the vehicle in the immediate vicinity of the power transfer induction coils will experience little to no exposure.

Momentum Dynamics and Oak Ridge National Laboratory therefore urge that the Commission not consider extending radiofrequency exposure limits to below 100 kHz. The evidence presented in IEEE C95.1 and IEEE C95.6 demonstrates that observable biological responses to electrical and magnetic fields at frequencies below 100 kHz occur at field intensities only well in excess of those expected in inductive wireless power transmission systems.

Should the Commission decide to extend electromagnetic field exposure limits to frequencies below 100 kHz, Momentum Dynamics and Oak Ridge National Laboratory respectfully advise that any new exposure limits be based upon the science and methodology

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[9] Applied Bioelectricity; From Electrical Stimulation to Electropathology, Reilly, Antoni, Chilbert, Sweeney, 2012, Springer, London.

[10] Electrostimulation; Theory Applications, and Computational Model, Reilly, Diamant, 2011, Artech House, Boston, MA.

presented in ICES IEEE C95.1 and C95.6 with special consideration of the limb exposure limits presented in these standards. Reliance should be placed on the ICES IEEE standards because:

- The IEEE uses science based physical and biological models for electric and magnetic induction phenomena.
- The IEEE standard has clearly stated objectives.
- The IEEE standard has a clear data trail from experimentally derived thresholds through physical and biological principals to recommended exposure limits.
- The IEEE standard has clearly stated, fully justified safety reduction factors.
- The IEEE standard employs well defined probability models to account for variation in human threshold tolerance.
- The IEEE standard provides separate, justified exposure limits for limbs.
- The IEEE standard has clearly defined population categories, general public and persons in controlled environments.

A detailed comparison, analysis and discussion of the ICES IEEE standard and the ICNIRP recommendation for electromagnetic field exposure in the 1 Hz to 100 kHz range authored by J. Patrick Reilly for Momentum Dynamics is attached as an Appendix.

Finally, in the NOI the Commission asks if extension of radiofrequency exposure regulation below 100 kHz is or could be in conflict with existing Commission regulation.[11] There is a strong likelihood of a regulatory exposure limit discontinuity at the 100 kHz splice point where the exposure limit methodology and metrology shifts from a thermal biological effects, Specific Exposure Ratio (SAR) methodology specified in power flux density (ie, mW/cm^2) on the high side of the splice point to a Peripheral Nerve Stimulation (PNS) methodology specified in terms of field strength Amperes/meter for magnetic fields and

[11] *See Supra*, n.2.

Volts/meter for electric fields below the splice point. A splice point regulatory discontinuity is not necessarily objectionable but it would be burdensome upon applications that occupy spectrum on both sides of the splice point.

Conclusion

The Commission should not extend radio-frequency exposure limits below 100 kHz. The likely administrative, economic, and opportunity costs would greatly exceed the expected societal benefits. No health or safety reason would justify such an extension and the likely costs would be significant, especially to the nascent emerging technologies that underlie resonant induction wireless power transmission for electric vehicles. According to the evidence presented in IEEE C95.1 and IEEE C95.6, observable biological responses to electrical and magnetic fields at frequencies below 100 kHz occur at field intensities only well in excess of those expected in inductive wireless power transmission systems.

In making its decision, the Commission should consider the effects of its actions upon the federal policy established by the President in Executive Order 13514 and other related federal mandates that require the replacement of internal combustion engine vehicles with alternative fuel vehicles on all federal properties.[12] We urge the Commission to consider the lack of electromagnetic field exposure health risks during resonant induction wireless charging and also the larger context of the known health risks associated with existing internal combustion engines. Unnecessarily extending radiofrequency exposure limits below 100 kHz would threaten delay and impede development of resonant induction wireless electric vehicle charging technology at a

[12] Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance, http://www.gpo.gov/fdsys/pkg/FR-2009-10-08/pdf/E9-24518.pdf, and also http://www1.eere.energy.gov/femp/pdfs/eo13514_fleethandbook.pdf

critical time and compromise current federal and state government policies that encourage early adoption of electric vehicles to, in part, alleviate the known health risks associated with internal combustion engines. At risk are well-defined national and societal economic and environmental benefits.

Should the Commission nevertheless decide to extend electromagnetic field exposure limits to frequencies below 100 kHz, the Joint Parties respectfully request that those new exposure limits be based upon the science and methodology presented in ICES IEEE C95.1 and C95.6. We further request that the Commission give careful consideration to the certification and validation difficulties inherent in resonant induction wireless electric vehicle charging.

Finally, should the Commission decide to consider extending electromagnetic field exposure limits to frequencies below 100 kHz, we recommend that those exposure limits include consideration of vehicle and ground substructure shielding effects. The presence of the vehicle fundamentally influences the performance of the technology and radiofrequency exposure to humans.

Respectfully submitted,

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APPENDIX

Limits on human exposure to electromagnetic fields in the frequency range 1 Hz – 100 kHz: The case for preference of the ICES standard over that of ICNIRP

J. Patrick Reilly

1.0 Introduction

Standards on human exposure to electromagnetic energy have been issued by two international organizations: The Institute of Electrical and Electronics Engineers (The *IEEE*, Headquartered in New York), and the International Commission on Non- Ionizing Radiation Protection (*ICNIRP*, headquartered in Europe, with internationally revolving Secretariats)[1]. The IEEE committee responsible for development of standards for electromagnetic exposure is known as the International Committee on Electromagnetic Safety (ICES).

The standards of both agencies cover the frequency range from zero hertz (static) to 300 GHz. This document focuses on the frequency regime from 1 Hz to 100 kHz, where the dominant mechanism of biological interaction is *electrostimulation*—the excitation of nerve and muscle by applied electrical energy. For frequencies above 100 kHz, the dominant mechanism is typically a thermal one.[2]

The ICES limits have been published in the frequency range 0 to 3 kHz in IEEE Standard C95.6-2002 (IEEE 2002), and from 3 kHz to 100 kHz in IEEE Standard C95.1-2005 (IEEE, 2005). Principles of electrostimulation forming the basis of IEEE C95.6 is found in (Reilly, 1998); those principles have since been updated (Reilly & Diamant, 2011). I led the IEEE working group responsible for IEEE C95.6-2002[3].

In 1998 ICNIRP published their original treatise on exposure limits (ICNIRP, 1998). The differences between the low frequency limits of ICES C95.6-2002 and ICNIRP-1998 were huge – at some frequencies differences as great as a factor of 100 were evident, despite the fact that both organizations reviewed largely the same literature, and their objectives were the same.

I subsequently published a paper on technical factors responsible for these large differences (Reilly, 2005), namely, the inclusion of different *in situ* metrics, interpretation of

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[1] The IEEE considers its limits as constituting a "Standard;" ICNIRP considers its limits as "Guidelines." This document will use the term *Standards* when referring to either of these. Neither organization has enforcement power. Adoption and enforcement of either standard is at the discretion of adopting agencies, whether governmental, or other.

[2] For pulsed electrostimulation, particularly of low duty factor, the dominance of electro-stimulation can extend well into megahertz frequencies. This paper focuses on continuous sinusoidal stimulus waveforms, where the dividing line is at about 100 kHz.

[3] IEEE Standard C95.6-2002 carries the acknowledgment: "Grateful appreciation is expressed to J. Patrick Reilly for his major contribution to this standard through technical development, his chairmanship of the Working Group responsible for its development, his drafting of this standard, and his gracious permission to adapt the material in this standard from his own numerous publications on this subject".

published literature and theoretical principles, selection of transition frequencies at which thresholds obeyed different power laws, lack of differentiation of limits for different tissues of the body, induction model, and treatment of "safety factors."

Revised ICNIRP guidelines were subsequently published (ICNIRP, 2010). That version drastically reduced extreme differences relative to ICES-2002 through inclusion of an *in situ* metric using the induced electric field, revision of transition frequencies much more in conformance with the ICES approach, differentiation of CNS and other tissue, substitution of an improved induction model, and reconsideration of published literature and theoretical principles. Despite the substantial reduction of differences, there still remain significant discrepancies between the two standards at frequencies below 100 kHz.

The ICES committee, in which I maintain active membership, recently sent a commentary to the FCC encouraging adoption of the ICES standard for FCC regulatory purposes (IEEE, 2013). That document treats the frequency range 30 MHz – 100 GHz, which is of interest to communication industries. Included was the statement: "These limits [IEEE C95.1] ... are in harmony with the ... ICNIRP guidelines for frequencies between 30 MHz and 100 GHz..." It should be noted that the ICES statement was not intended to apply to frequencies below 100 kHz. This paper treats that frequency domain.

2.0 Comparison of ICES and ICNIRP from 1 Hz – 100 kHz

ICES and ICNIRP express exposure standards in terms of *in situ* and environmental limits. The *in situ* limits are termed *Basic Restrictions* (BRs) by both agencies; the environmental limits are called *Maximum Permissible Exposure* (MPE) limits by ICES, and *Reference Levels* (RLs) by ICNIRP. As a general rule, it is much easier to determine compliance with the MPEs than the BRs. The MPE limits ensure that the BRs are satisfied. However, exceedance of an MPE limit does not necessarily mean the BRs are exceeded. The user has the option of demonstrating conformance to the BRs in that case through measurement or calculation.

Table 1 lists BR limits of ICES, which are differentiated among the tissue types as: brain; hands wrist, feet & ankles; and "other tissue.[4] The ICES standard also lists separate BRs for the heart, however, for brevity, these are omitted from Table 1. In general, adverse simulation thresholds of the heart are greater than those for peripheral nerve. As seen in Table 2, ICNIRP differentiates between only 2 tissue types: the brain, and "other." Both organizations provide separate limits according to two tiers – one of these is identified as the *General Public*; the other is identified as *Individuals in Controlled Environments* by ICES, and *Occupational Exposure* by ICNIRP.

[4] In some cases the units or formats of the original data expressed in Tables 1 – 4 have been converted to other forms for clarity and consistency.

Table 1. ICES Basic Restrictions, f = 1 Hz – 100 kHz (from IEEE (2002; 2005)

Exposed tissue	General Public		Controlled Environment	
	Freq. Range (Hz)	E_{BR} (V/m)	Freq. Range (Hz)	E_{BR} (V/m)
Brain [(a)]	1 – 20	5.8×10^{-3}	1 – 20	1.77×10^{-2}
	20 – 1k	$2.9 \times 10^{-4} f$	20 – 1k	$8.85 \times 10^{-4} f$
Hands, wrists, feet, ankles	1 – 3.35k	2.10	1 – 3.35k	2.10
	3.35k – 100k	$6.27 \times 10^{-4} f$	3.35k – 100k	$6.27 \times 10^{-4} f$
Other tissue [(b)]	1 – 3.35k	0.701	1 – 3.35k	2.10
	3.35k – 100k	$2.09 \times 10^{-4} f$	3.35k – 100k	$6.27 \times 10^{-4} f$

Notes:

(a) BRs for brain are based on synaptic activity alteration. The upper limit of such interaction is not known. An upper limit of 1 kHz has been assumed in table.

(b) ICES BRs for the heart are not shown here for brevity. “Other tissue” is everything except brain; heart; hands, wrist, feet, & ankles.

(c) Data expressed as *RMS* values.

(d) In formulas, f is expressed in Hz.

Table 2. ICNIRP Basic Restrictions, f = 1 Hz – 100 kHz (from ICNIRP 2010)

Exposed tissue	General Public		Occupational Environment	
	Freq. Range (Hz)	E_{BR} (V/m)	Freq. Range (Hz)	E_{BR} (V/m)
Brain	1 - 10	$0.1/f$	1 - 10	$0.5/f$
	10 - 25	0.01	10 - 25	0.05
	25 – 1k	$4 \times 10^{-4} f$	25 – 400	$2 \times 10^{-3} f$
	1k – 3k	0.4	400 – 3k	0.8
	3k – 100k	$1.35 \times 10^{-4} f$	3k – 100k	$2.7 \times 10^{-4} f$
Other tissue[(a)]	1 – 3k	0.4	1 – 3k	0.8
	3k – 100k	$1.35 \times 10^{-4} f$	3k – 100k	$2.7 \times 10^{-4} f$

Notes:

(a) “Other tissue” includes everything other than brain. No special provisions made for limbs.

(b) Data expressed as *RMS* values.

(c) In formulas, f is expressed in Hz.

Table 3. ICES Maximum permissible exposure (MPE) levels to magnetic field exposure, f = 1 Hz – 100 kHz (from IEEE 2002; 2005).

Exposed body part	Freq. Range (Hz)	*RMS* MPE limit, B_{MPE} (mT)	
		Gen. Public	Restr. Env.
Head & torso	1 - 20	18.1/f	54.3/f
	20-759	0.904	2.71
	759-3.35k	687/f	2060/f
	3.35k – 100k	0.205	0.615
Limbs	1 – 10.7	353	353
	10.7 – 3.35k	3790/f	3790/f
	3.35k – 100k	1.13	1.13

Notes:
(a) In formulas, f is expressed in Hz.

Table 4. ICNIRP Reference Levels (RLs) for exposure to time-varying magnetic fields, f = 1 Hz – 100 kHz. No distinction made for exposed body part.

General Public		Occupational Exposure	
Freq. Range (Hz)	Mag. flux density (mT)	Freq. Range (Hz)	Mag. flux density (mT)
1 - 8	$40/f^2$	1 - 8	$200/f^2$ (b)
8 - 25	5/f	8 - 25	25/f
25 – 400	0.2	25 - 300	1.0
400 – 3k	80/f	300 – 3k	300/f
3k – 100k	0.027	3k – 100k	0.10

Notes
(a) In formulas, f is expressed in Hz
(b) ICNIRP (2010) erroneously lists frequency multiplier as f rather f^2.
(c) Units of magnetic flux density in this table are in mT, rather than T as in ICNIRP document.

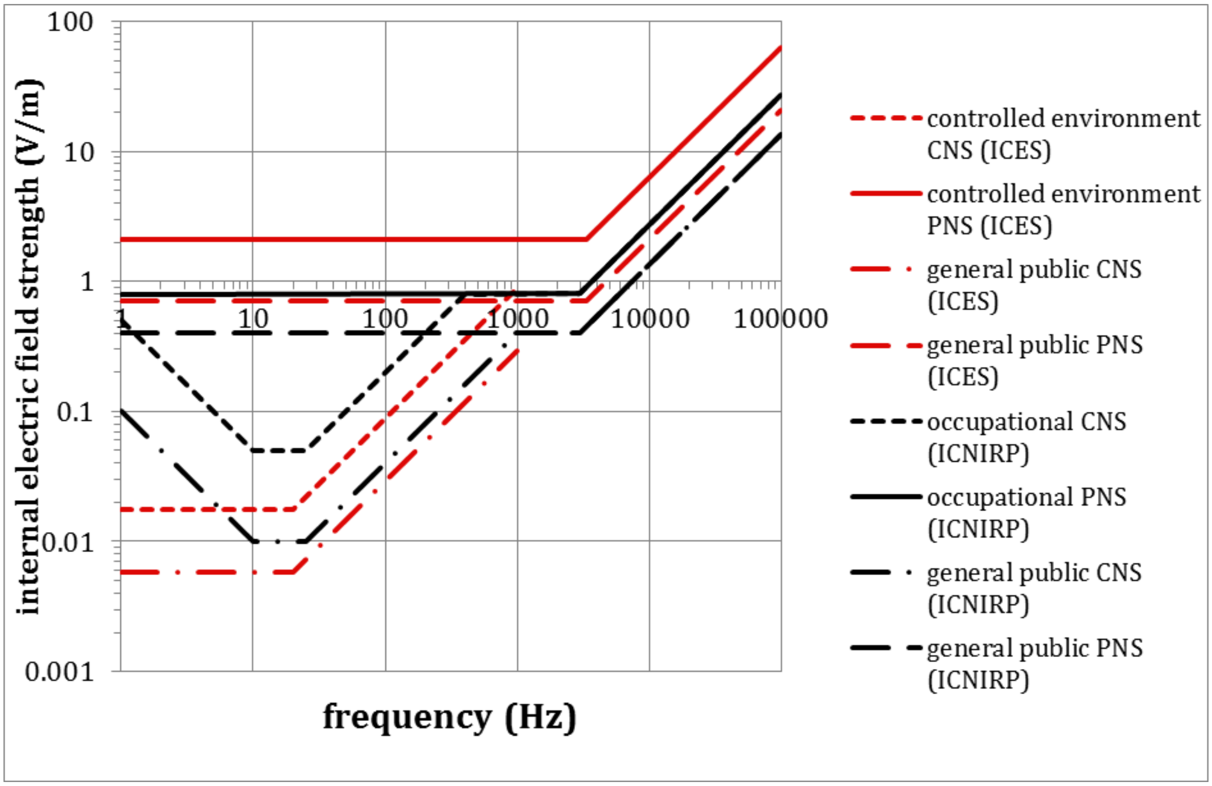

Figure 1. Basic Restrictions of IEEE C95.6-2002 (red) and ICNIRP-2010 (black) in the frequency range 1 Hz – 100 kHz.

Table 3 lists the MPE limits of ICES. In this case, allowable exposure of the head & torso (effectively, "whole-body" exposure) is differentiated from the limbs. However, ICNIRP makes no such differentiation (Table 4).

Figure 1 compares the ICES and ICNIRP BRs. With exposure of the brain at frequencies above a few hertz, the ICES limits are lower than those of ICNIRP, typically by a factor of 2 – 3. For peripheral nerve stimulation, the ICES limits exceed those of ICNIRP by a factor of about 2. As the frequency drops below10 Hz, ICES becomes increasingly conservative with respect to ICNIRP.

Figure 2 compares the environmental limits of the two organizations. Excepting exposure of the limbs in the case of ICES, the MPE limits assume exposure of the head and torso. Consequently, the MPE limits would be dominated by the most sensitive tissue. Excepting exposure of the limbs, the ICES limits exceed those of ICNIRP by factors of about 3 – 5 over most of the frequency spectrum. For exposure of the limbs but not the head and torso at frequencies above 1000 Hz, ICES would allow greater

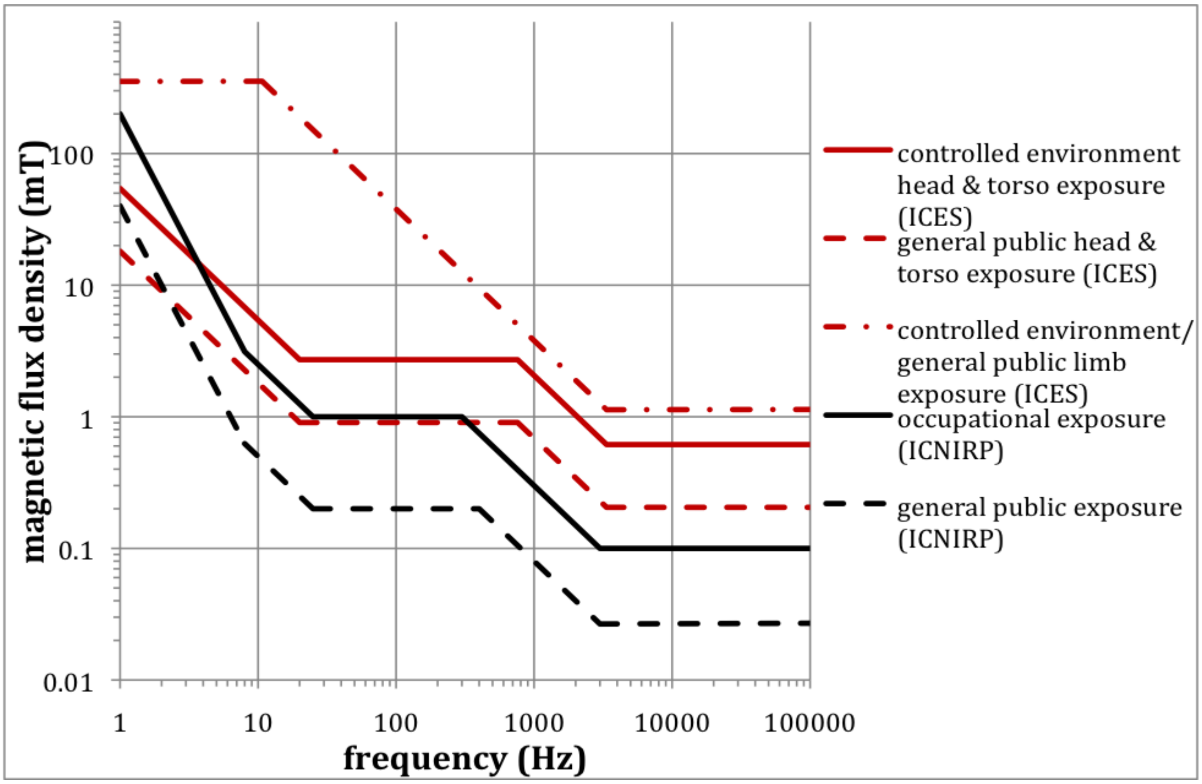

Figure 2. Maximum Permissible Exposure (MPE) levels of ICES standard (red) and Reference Levels (RLs) of ICNIRP (black).

exposures by a factor of about 10 relative to ICNIRP. Below 1000 Hz, ICES limits grow to a factor of about 50 above those of ICNIRP. The reason for such a large discrepancy is largely due the fact that extremity exposure does not include the brain, which is much more sensitive to electrostimulation than other tissue at frequencies below 1000 Hz,[5] and the induction area of the limbs is smaller than that of the head and torso.

3.0 The case for adoption of the ICES standard over that of ICNIRP

Whereas the 2010 revision of the ICNIRP standard has drastically reduced differences relative to the ICES standard, significant differences remain, particularly at frequencies below 100 kHz, where electrostimulation is the dominant mechanism of interaction. The discussion below addresses these discrepancies, and makes a case for adoption of the ICES Standard over that of ICNIRP. The focus is on the frequency regime below 100 kHz.

The rationale for the ICES electrostimulation limit is fully developed in IEEE C95.6-2002. Although that document provides limits only up to the frequency of 3 kHz, the rationale behind the limits is equally applicable to electrostimulation effects at much higher frequencies, including the upper limit of 100 kHz discussed here.

[5] Such CNS sensitivity is due to the effects of the induced *in situ* electric field at synaptic processes within the brain.

For an overview the derivation of ICES BRs, refer to Table 10 of IEEE C95.6, which provides numerical data on the median thresholds of just-noticeable reaction, the adverse reaction level, a factor to convert median thresholds low probability reaction thresholds, safety factors, and the final BR value. The text provides the justification for these data, including experimental references. Figure 1 of C95.6 provides an overview of the derivation of MPE levels. Appendix B of the standard describes the mathematical induction model used to derive the MPEs from the BRs.

3.1 Objective and purpose of the standards

Both organizations state the objective is to protect against established adverse health effects of an acute nature.

ICES clearly identifies adverse effects in this frequency regime as aversive or painful electrostimulation, and it provides a complete explanation of the experiments and principles whereby the specific limits are derived.

The endpoints requiring protection in the ICNIRP limits are unclear. Although ICNIRP states its purpose is to protect against adverse effects, specific adverse reactions are not defined. For example, in discussing protection afforded by the RLs, ICNIRP refers to "PNS effects" (p. 828, col. 1) but does not specify what these effects are – whether perception, discomfort, pain, motor twitch, limits of tolerance, or something else.

3.2 Data trail leading to BR and MPE limits

ICES provides a complete data trail leading from experimental and theoretical sources to the actual limits, with every step and assumption clearly numerically defined as mentioned above. Consequently, it is possible for someone to follow the ICES reasoning, to duplicate or repudiate those results, or to determine the consequences if new data were to become available, or if other assumptions were made.

This is not the case in the ICNIRP standard. In general, it is impossible for a reader to determine how the BRS values were determined. ICNIRP does discuss various publications that examined electrostimulation effects from electromagnetic field exposure, however, the connection between findings in the cited studies and the ICNIRP limits is unclear. For instance the document states (p. 825, col. 1) that exposure to the head and body in controlled environments should be limited to 800 mV, which includes a "reduction factor" of 5 below a stimulation threshold of 4 V/m.

Such a statement begs the questions (unanswered in the ICNIRP standard): To what frequency does the stated threshold apply? How did ICNIRP extrapolate this result to other frequencies, and what is the justification for such extrapolation? Is the 4 V/m value the threshold of perception as the statement implies? If so, how can this be understood as an adverse reaction? What probability rank among the population does 4 V/m apply to – 50%? 1%? The lowest observable effect level? The lowest observable adverse effects level? Is 4 V/m a peak or an *RMS* value, and how does this comport with experimental values?

3.3 Safety/Reduction factors

To develop an exposure limit, a reduction factor is typically applied to what is considered an adverse effects level. ICES and ICNIRP adhere to different philosophies in applying such margins.

In developing BRs, ICES identifies a median adverse reaction level, as noted in Table 10 of IEEE C95.6, column D.[6] That value is converted to a low probability (1% or less) reaction level by reducing the median value by a Probability Factor, F_P (column E) That value is further reduced by applying a "Safety Factor," F_S (Column F), which is intended to account for various uncertainties. The total reduction is the product F_P F_S, which should be compared with what is called a "Safety Factor" in the standard at higher frequencies.[7] For most of the effects under consideration, the product F_P F_S = 1/3 for the controlled environment and 1/9 the general public (where the factors are multipliers).

ICNIRP applies *Reduction Factors* of 5 (occupational) and 10 (general public) to a level where "transient effects are noted". We do not know what adverse effect this refers to, whether it is adverse, and whether the level before the reduction factor is a median value, or something else (see also Section 3.2).

3.4 Probability models

Electrical reaction thresholds vary from person to person. The variability of electrical thresholds among subjects is found to be considerably greater than variations in a single subject measured repeatedly over time. Intersubject variations fit well to the lognormal statistical model (Reilly, 1998, pp. 282-290; Reilly & Diamant, 2011, pp. 111-114).

The ICES standard recognizes such statistical relationships, and incorporates probability factors to account for such variations. Probability levels associated with reaction thresholds and the limits of the standard are defined.

ICNIRP does not refer to intersubject variations. It is unclear what phenomena are included in its "Reduction Factors." It does not discuss probabilities associated with reaction thresholds that are mentioned throughout the standard.

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[6] The ICES Adverse Reaction Level is derived from a just noticeable threshold (column B of Table 10 in IEEE C95.6) by applying a multiplier that depends on the particular tissue under consideration (column D). For peripheral nerve stimulation (PNS) a multiplier of 1.45 converts the perception threshold to a pain threshold. For central nerve stimulation (CNS), the just noticeable reaction is considered adverse, i.e., F_S = 1.

[7] In IEEE C95.6, the product F_P F_S = (1/3) x (1/3) = 1/9 in most cases for the general public, and is 3 for the controlled environment. To compare these reduction factors to the "Safety Factor" applied to specific absorption rates (SAR) to higher frequencies, note that the SAR safety factor is applicable to the square of the *in situ* field, whereas the product F_P F_S is the magnitude of the field. One would have to square the product F_P F_S to compare it with an SAR safety factor.

3.5 Separate limits for exposure of the limbs

The ICES limits (Tables 1 & 3) have separate specifications for exposure of the limbs. This is to allow for nonuniform exposures in which the limbs may be preferentially exposed, but with relatively little exposure to the head and torso. An example would be the case of an attendant in a MRI examination who places his hands and arms into the core, possibly to minister to the patient, but with very little exposure to his head or torso.[8] The exclusion of the examiner's head from exposure is particularly significant, since the exposure limits for the brain at low frequencies are particularly low. It would be overly conservative to require that an examiner comply with exposure limits for the brain, when only his arms are exposed. The MPEs for the limbs are lower than whole body limits, not only because the brain is not included, but also because the magnetic induction area of the limbs is much smaller than that of the head and torso.

ICNIRP makes no separate provisions for exposure of the limbs.

3.6 Definition of exposed populations

IEEE C95.6-2002 provides limits for two categories of exposed individuals, defined as follows:

> *General Public*: All individuals who may experience exposure, except those in controlled environments.
>
> *Controlled Environment:* An area that is accessible to those who are aware of the potential for exposure as a concomitant of employment, to individuals cognizant of exposure and potential adverse effects, or where exposure is the incidental result of passage through areas posted with warnings, or where the environment is not accessible to the general public, and those individuals having access are aware of the potential for adverse health effects.

According to these definitions, persons in occupational settings, and persons in controlled environments are not necessarily the same. For instance, ICES would not consider an office worker, or a grounds keeper in a facility with an electromagnetic field source to be subject to the Controlled Environment limits, unless special conditions were met.

In contrast, ICNIRP recognizes two categories: *General Public,* and *Occupational*, where "Occupational exposure... refers to adults exposed to time-varying ... fields ... generally under known conditions and as a result of performing their job activities" (p. 824, col. 2). This definition would include individuals who would be classified by ICES as members of the general public.

[8] The ICES standard does not apply to patients undergoing medical procedures, in which electromagnetic energy is administered, but it would apply to practitioners, who would be considered as persons within a controlled environment.

3.7 Induction models

Magnetic field MPEs are derived from the BRs using an induction model. IEEE standard C95.6 uses an ellipsoidal uniform conductivity (EUC) model to fit the body or body part under consideration. The EUC model supports an analytic solution to the induced electric field (E-field) at any point within the ellipsoidal volume with arbitrarily high precision (see IEEE C95.6-2002, pp. 42-42; Reilly, 1998, pp. 363-366).

ICNIRP-2010 uses a Finite Difference Time Domain (FDTD) detailed anatomical induction model.[9] FDTD models allow one to determine the distribution of the induced electric field (E-field) with high resolution, and with the ability to separately determine the E-field distribution within individual organs.

A difficulty with FDTD results is the presence of numerical artifacts at the interfaces between regions having disparate conductivity, and particularly at air/tissue interfaces (Reilly & Diamant, 2011, pp. 122-128). Such artifacts typically exaggerate the maximum E-field at the interfaces. A common method of dealing with these artifacts is simply to discard a small percentage of the largest values in each organ, such as the largest 1 percentile values, and retaining as the largest value (the 99th percentile rank) to represent the "maximum" value. Analytic studies show that such methods for filtering out artifacts in FDTD solutions yield considerably different results, depending on details of the modeling approach (De Santis, 2013). It is not clear the extent to which such methods may discard valid data, or accept invalid artifacts.

This method of artifact filtering may be satisfactory when determining organ averages, or averages within specified volumes, as is done at high frequencies where the SAR metric may be appropriate. In such cases, large-value artifacts may have only a modest effect on the average. However, with electrostimulation phenomena, the potential for exciting a neuron more nearly depends on the maximum E-field value along its extended length, in which case a single artifact or a discarded valid point may introduce a significant error.

Compounding the difficulty of handling artifacts in the ICNIRP methodology is its specification of volume averages for determining electrostimulation potential (p. 825, col. 2), rather than a line average over a small extent (5 mm in the ICES standard), which is appropriate for assessment of neural excitation (Reilly & Diamant, 2003; Reilly & Diamant, 2011, pp. 117 – 118).

[9] The FDTD model used in ICNIRP's 2010 paper is a considerable improvement over the simple circular loop model which was used to represent the body in the 1998 paper.

4.0 Conclusions and recommendations

Human exposure limits to electromagnetic fields in the frequency range 1 Hz – 100 kHz have been developed by ICES and ICNIRP. This document presents the case for preference of the ICES limits. The ICES standard is superior to that of ICNIRP in a number of categories, as summarized below.

(1) Objectives. ICES clearly states the objectives to avoid adverse reactions, which are defined as aversive or painful reactions. ICNIRP states that avoidance of adverse reactions is a goal, but it is not clear what it means by "adverse," and whether the goals are actually achieved in its limits.

(2) Data trail. The ICES standard provides a clear path from experimental adverse thresholds and theoretical principles to the limits of the standard. In ICNIRP, the connection between laboratory or theoretical studies and the limits of the standard are not clear.

(3) Safety/reduction factors. ICES makes clear the rationale behind reduction factors, and identifies separate components of those factors. ICNIRP does not explain the rationale behind its reduction factors.

(4) Probability models and treatment. ICES makes clear the probabilities associated with reaction thresholds, including the limit values. ICNIRP does not acknowledge variations among subjects, nor does it define the statistical probabilities associated with its limit values.

(5) Exposure of the limbs. ICES provides separate limits for exposure of the limbs. ICNIRP does not.

(6) Definition of exposed populations. ICES defines the two categories of exposed populations: *General Public*, and *Persons in Controlled Environments*. In the ICNIRP standard, the *Occupational Exposure* group would include individuals considered as members of the general public by ICES.

(7) Induction Models. ICES uses an EUC model to derive MPE levels from the BRs. That model provides reasonably accurate values of the induced E-field within the body, and is free of artifacts. ICNIRP uses an FDTD model that is known to produce large-valued artifacts. ICNIRP attempts to discard these artifacts, however, the extent to which such procedures may discard valid data or accept invalid artifacts is unknown.

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Curriculum Vitae

AFFILIATION	Principal Staff, The Johns Hopkins University, Applied Physics Laboratory (part-time appointment); Metatec Associates (president & founder).
EDUCATION	1967 - THE GEORGE WASHINGTON UNIVERSITY, Washington, D.C. M.S.E. in Electrical Engineering and Applied Science. Thesis, in radar signal processing, was adapted as part of a reference book on radar theory. 1962 - UNIVERSITY OF DETROIT, Detroit, Michigan B.S.E. in Electrical Engineering (cum laude)

SUMMARY OF EXPERIENCE

1986 - Present	President and Founder, Metatec Associates. Performs research and consulting in bioelectric phenomena, bioelectric devices, and electrical safety. Serves as consultant to federal, state, and private agencies concerning exposure to electric currents and electromagnetic fields, including analysis of bioelectric therapy and diagnosis, electrical safety, forensic science, and expert witness testimony. Developed electrical and electromagnetic health and safety standards, including IEEE Standard C95.1 on electromagnetic exposure to workers and the general public (IEEE C95.6), and USFDA guidelines for patients in Magnetic Resonance Imaging. Chaired IEEE Mechanisms Working Group on electromagnetic standards; designed and taught courses on electrical standards and safety.
1962 – 2011	THE JOHNS HOPKINS UNIVERSITY, Applied Physics Laboratory (APL), Laurel, MD. The following paragraphs refer to experience while at APL (Part-time appointment from January, 1998 to December, 2011).
1984 - Present	Principal Staff Engineer Supervisor, Environmental Modeling Section; Biomedical Programs Coordinator, Air Defense Systems Department. Project leader for various studies including: radar and infrared (IR) propagation and scattering; radar and IR detection and tracking systems. Chaired NATO Working Group to develop radar clutter models. Developed R&D program in IR technology for parent Branch. Conducted bioelectric research. Carried out biomedical programs coordination and program development within department. Representative for electromagnetic standards-setting activities.
1975 - 84	Supervisor, Environmental Assessment Group, Electromagnetics and Acoustics Section. Directed an interdisciplinary team in applied research on electric shock and other phenomena related to electromagnetic and acoustic interactions with biological and environmental systems. Research efforts directed to environmental effects of electric power facilities. Management activities included proposal preparation, program planning, budgeting and liaison with program sponsors. Participated in various regulatory hearings, in capacities including expert witness testimony, assistance in cross-examination, and the preparation of briefs.

1972 - 75 Supervisor, Sonar Analysis Section - Conducted studies on underwater acoustic detection systems. Activities included theoretical and experimental evaluation of passive acoustic detection systems. Prepared a comprehensive, five-year work plan for the parent Underwater Acoustic Group (30 personnel), including budgetary, staffing and technical considerations.

1962 - 72 Staff Engineer/Supervisor, Radar Analysis Section. Involved in various experimental and theoretical studies on advanced radar systems, including signal processing, system analysis, research on radar reflections from targets and the natural environment (rain, terrain, etc.) Portions of this work were published in a standard reference book on radar theory. Other activities included satellite navigation studies, and the development of a system for the recognition of airborne sounds. Promoted to supervisor of the Radar Analysis Section in 1971.

PROFESSIONAL ACTIVITIES

* Invited speaker and panelist at various international meetings.
* Life-Fellow Member, Institute of Electrical and Electronics Engineers.
* Member, The Bioelectromagnetics Society (BEMS), 1983 -present. Participant on various working groups and program planning committees.
* Member, Committee on Man and Radiation (COMAR), 1993-1997.
* Member, Magnetic Resonance Safety Committee, American College of Radiology, 1993-1998.
* Member, IEEE International Commission on Electromagnetic Safety, and Subcommittees 3 and 4; Chairman of Mechanisms Working Group, SC-3, 1994-present; principal author IEEE Standard C95.6,
* Director of task forces responsible for the development of IEEE publications on transmission line corona and field effects and on electric shock. Presented related lectures within IEEE-sponsored courses.
* Service as a papers referee for numerous journals.
* Consultant to state and federal agencies for proposal review.
* Chaired sessions at various technical conferences.
* Member, Electrotherapy Standards Committee, American Physical Therapy Association, 1997-1998.
* Consulting member, International Commission on Non-Ionizing Radiation Protection, 2001 – 2004.

AWARDS *1986, 1989, 1996 - Appointed to the Stuart S. Janney Fellowship of the Johns Hopkins University for bioelectric research activities. *Outstanding Publications Award, The Johns Hopkins Applied Physics Laboratory: 1988 (pub. # 64), 1990 (pub. #69), 1991 (pub. #76), and 1992 (pub. #79). *Out-standing publication award, American Society of Agricultural Engineers, 1995 (pub. #94). *Elected in 1998 as Fellow of IEEE "*for furthering the state of knowledge concerning human reactions to electric current and electromagnetic fields, with application to medical devices, human hazards, and safety standards*." *Awarded Research Fellowship (2009-2011) by the Oak Ridge Institute for Science and Education (ORISE) as a computational initiative of the U.S. Food and Drug Administration.

TEACHING

"Hazards and Mechanisms " Section of short course on Electromagnetic Hazards, sponsored by Electromagnetic Energy Association and Rutgers University, Continuing Education Department, 1993, 1994, 1995, 1996; University of Texas, 1998, 2000; designed and taught seminar course on electrical safety, 2001; designed and taught one-day course on electro-magnetic exposure standards, March '04 (Ottawa, Canada), June '04 (Wash. DC), December '04 (San Antonio, Tx), and June '05 (Dublin, Ireland); Government-sponsored lecturer at public hearings on electrical effects of stun weapons (Vancouver, BC 2006 & 2008; New Brunswick, 2007).

PUBLICATIONS

Over 145 published works, including reference books, journal papers, book chapters, professional meeting abstracts, and technical reports. Principal Author of *Electrostimulation, Theory, Applications, and Computational Model* (Artech House, 2011); Author of *Electrical Stimulation and Electropathology* (Cambridge University Press, 1992); author of *Applied Bioelectricity: from Electrical Stimulation to Electropathology* (Springer-Verlag, 1998); co-author of *Radar Design Principles* (McGraw-Hill Book Co., 2nd ed., 1991).

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Instruction:

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"Electrical Safety: Principles and Applications," (Design and presentation of 3.5-day intensive course, with W. Skuggevig) May 8-11, 2001, sponsored by John Deere Inc.

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Canadian Government-sponsored lecturer at public hearings on electrical effects of stun weapons (Vancouver, BC 2006 & 2008; New Brunswick, 2007).

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